# A Roadmap for Damage Tolerance Implementation in Rotorcraft


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**Atlantic City International Airport, New Jersey**

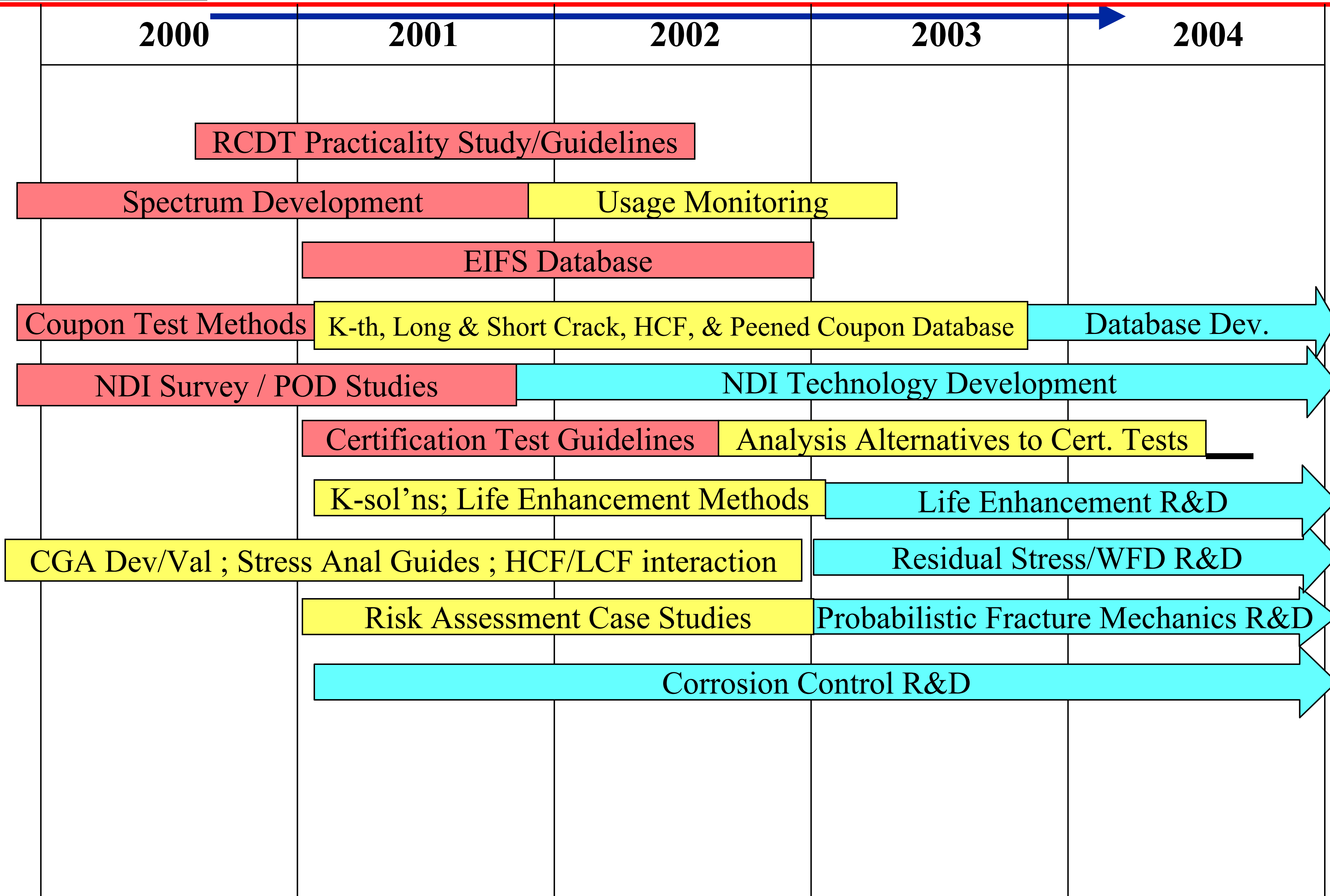

**Presented to**

**WORKSHOP ON FATIGUE DESIGN OF HELICOPTERS**

**12-13 SEPTEMBER 2002**

**PISA, ITALY**

# ROTORCRAFT DAMAGE TOLERANCE (RCDT) ROADMAP



# Presentation Outline

- Rotorcraft damage tolerance (RCDT) R&D accomplishments and research results –

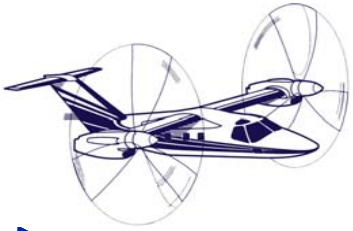
- Health and Usage Monitoring Systems (HUMS) accomplishments and research results –

# Documentation

## SOW's:

- RC Usage Spectrum and Fatigue Life Data Development
- Equivalent Initial Flaw and Crack Size
- Development and Validation of Crack Growth Models and Life Enhancement Methods for RC Damage Tolerance
- Development and Validation of an Automated Small-Crack Detection Monitoring System
- Establish Structural Monitoring Requirements for HUMS

# Sponsors



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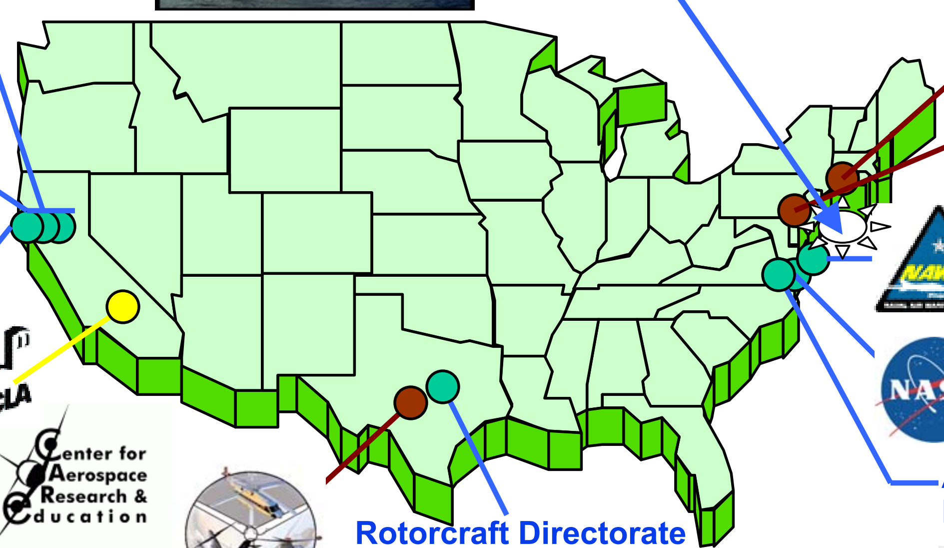
# Partnerships/Collaborations in RCDT and HUMS Research




**A joint RCDT program with RITA, academia, DOD, and other government research agencies to develop and validate mutually agreed-upon technologies that will address rotorcraft damage tolerant design and certification issues.**

# RCDT Accomplishments

- Identified specific issues and potential analytical approaches for addressing these issues.
- Identified and quantified rotorcraft unique Principal Structural Elements (PSE's) using a DT method to provide potential guidelines for RCDT design, certification, and management.

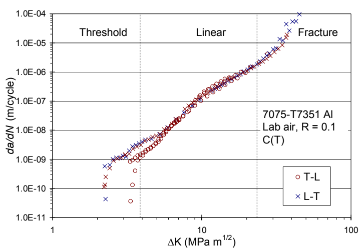
# RCDT Accomplishments
## Target Research Areas

Material crack growth data

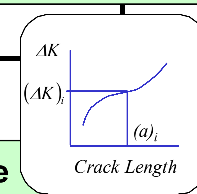
Component geometry and stress distribution

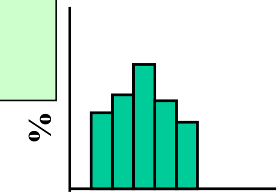
Load spectrum and limit load

da/dN

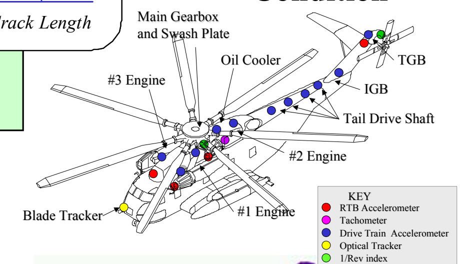



$\Delta K$th




Condition




Rogue crack size, $a_0$

Determine stress intensity factor, $\Delta K(a_0)$

$\Delta K$th = crack growth threshold

$\Delta K(a_0) < \Delta K$th ?

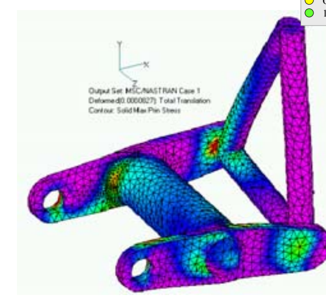
YES

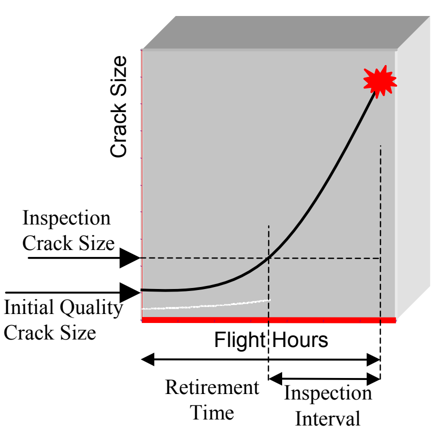
No crack growth

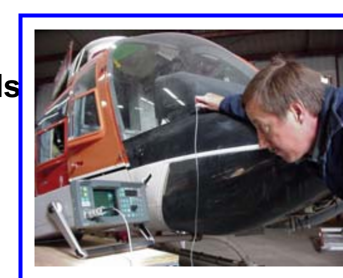
NO

Crack growth

- Analysis
- Component testing
- Determination of inspection intervals





# Damage Tolerance Analysis Flow

# RCDT Accomplishments

## Comparison Study of DT/SL on PSE's

Bell Helicopter TEXTRON
A Subsidiary of Textron Inc.

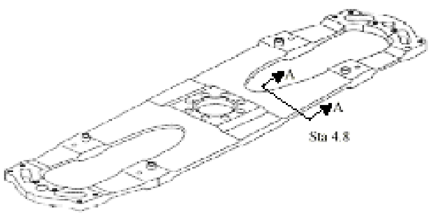


Fig. 6. Main rotor yoke geometry.

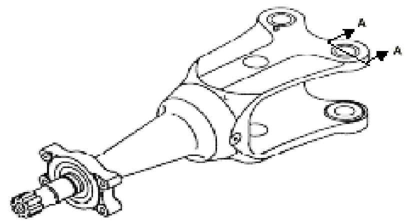


Fig. 9. Main rotor spindle.

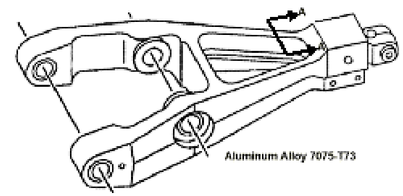


Fig. 12. Collective lever.

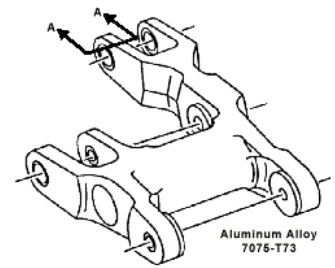


Fig. 15. Rephase lever.

Table 1. Summary of damage tolerance results for the four PSEs.

| Helicopter PSE | Baseline safe-life retirement time | Baseline damage tolerant crack growth life (Ref. 2) | Calculated damage tolerant crack growth life [a] | Calculated damage tolerant inspection interval [a] | Material | Weight increase over baseline assembly (%) |
|---|---|---|---|---|---|---|
| Main rotor yoke | 5000 hrs | 20 hrs | N/A [b] | N/A [b] | 6AL-4V titanium with BSHTOA | N/A [b] |
| Main rotor spindle | 10,000 hrs | 143 hrs | > 20,000 hrs | 10,000 hrs | 15-5 stainless steel | 4.6% |
| Collective lever | 10,000 hrs | 13 hrs | No crack growth | No inspection required | 7075-T73 aluminum | 22% |
| Rephase lever | 5000 hrs | 78 hrs | No crack growth | No inspection required | 7075-T73 aluminum | 15% |

[a] Crack growth life based on limited analytical study results for theoretical designs of each PSE.

[b] Composite material might be an alternative for the main rotor yoke to potentially meet damage tolerance requirements with a 5,000-hour inspection interval.

# RCDT Accomplishments

## Spectrum Development & Usage Monitoring

- Investigated and developing mission spectrum data for modern helicopter systems to improve the accuracy of the calculations used in the predictions of crack growth in rotorcraft structural components.

- Continuing to expand the monitoring of usage data and monitoring methods for DT applications.

# RCDT Accomplishments

## Helicopter Usage Spectrum Development

### TABLE 1. HELICOPTER USAGE SPECTRUM

| REF. NO. | MISSION | MODEL | ORGANIZATION/SOURCE | PECIAL EQUIPMENT | ON GROUND | | HIGE | | HOGE | | MANEUVER | | STRAIGHT & LEVEL | | SINGLE ENGINE | | AUTO ROTAT | | SLOPE LANDING | | STARTS | | STOPS | | GAG | | TORQUE EVENTS | | NO. FLIGHTS | | NO. LNDGS | | CONV. | | PRESS CYCLE | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % | OPFH |
| 1 | CAM 6 DESIGN USAGE SPECTRUM | | CIVIL AERONAUTICS | | 1.5 | | 4 | | | | 19.5 | | 64.5 | | | | 10.5 | | | | | | | | | | | | | | | | | | | |
| 2 | OVERALL SORTIE | BELL 212 | BRISTOW HELICOPTERS | | 12 | | 16 | | 10.5 | | 10 | | 49 | | 1.5 | | 0.5 | | 0.5 | | | 1.1 | | | | 4.1 | | 5.2 | | | | | | | | |
| 3 | 212 DESIGN USAGE SPECTRUM | BELL 212 | BELL HELICOPTER TEXTRON | | 1 | | 5.8 | | | | 15.8 | | 77 | | 0.4 | | 0.5 | | | | | | | | | 4 | 26 | | | | | | | | | |
| 4 | OFFSHORE OIL SUPPORT (MEASURED OPERATIONAL DATA) | BELL 212 | PETROLEUM, AIR LOGISTICS, AND HOUSTON HELICOPTERS | | 7.71 | | 2.94 | | | | 6.37 | | 77.4 | | 0.03 | | 5.2 | | | | | 2.96 | | | | | | | | 2.53 | | | | | | |
| 5 | | BELL 412 | BRISTOW HELICOPTERS | | | | | | | | 8.2 | | 61.1 | | 0.02 | | 0 | | 0.2 | | | | | | | 3.25 | | | | | | 0.73 | | | | |
| 6 | ATLANTA SHORT HALL | BELL 412 | PETROLEUM HELICOPTERS | | 0 | | 7.3 | | | | 28.3 | | 64.4 | | 0 | | 0.03 | | | | | | | | | | | | | | | | | | | |
| 6 | OFFSHORE OIL SUPPORT GULF COAST MISSION | BELL 412 | PETROLEUM HELICOPTERS | | 0 | | 3.7 | | | | 14 | | 82.2 | | 0.04 | | 0.02 | | | | | | | | | | | | | | | | | | | |
| 7 | UTILITY MISSION MORGAN CITY | BELL 412 | PETROLEUM HELICOPTERS | | 0 | | 2.3 | | | | 12.4 | | 85.3 | | 0 | | 0.02 | | | | | | | | | | | | | | | | | | | |
| 8 | 412HP DESIGN USAGE SPECTRUM | BELL 412HP | BELL HELICOPTER TEXTRON | | 0 | | 4.1 | | 14.5 | | 20.4 | | 60.8 | | 0.2 | | 0.05 | | | 0.4 | | | | | | 4 | | 26.0 (1) | | | | | | | | |
| 8 | 412CF DESIGN USAGE SPECTRUM | CA 412CF | BELL HELICOPTER TEXTRON | | | | | | | | | | | | | | | | | 0.25 | | | | | | | | | | | | | | | | |
| 9 | 430 DESIGN USAGE SPECTRUM | BELL 430 | BELL HELICOPTER TEXTRON | | 2 | | 4.4 | | | | 14.1 | | 78 | | 0.2 | | 13 | | | | | | | | | 4 | | 16.0 (1) | | | | | | | | |
| 10 | V-22 DESIGN USAGE SPECTRUM | BB V-22 | BHT & BOEING HELICOPTERS | | 1 | | 6 | | | | 33.2 | | 58.4 | | | | 14 | | | | | 1 | | 1 | | 4 (2) | | | | 3 | | 3 | | 10 | | |
| 11 | 609 DESIGN USAGE SPECTRUM | BA 609 | BHT & AGUSTA | | | | | | | | | | | | | | | | | | | 4 | | 4 | | 2.0 (3) | | 8 | | 1.25 | | 1.25 | | 4.0 (4) | | 1 |
| 12 | LYNX DESIGN MISSION MIX | LYNX | WESTLAND HELICOPTER LTD. | | 20 | | | | | | 10.4 | | 55.1 | | 3 | | 3.2 | | | | | | | | | | | | | 5 | | 5 | | | | |
| 14 | HIGH PRODUCTIVITY LOGGING MISSION | K-1200 | KAMAN AEROSPACE CORP. | | | | | | | | | | | | | | | | | | | | | | | | | 40.0 (5) | | | | 1.0 (6) | | | | |
| 14 | FIREFIGHTING MISSION | K-1200 | KAMAN AEROSPACE CORP. | UNDERSLUNG WATER BUCKET | | | | | | | | | | | | | | | | | | | | | | | | 22.0 (7) | | | | 1.0 (8) | | | | |
| 15 | EMERGENCY MEDICAL SERVICE (EMS) | | | | | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 16 | GATHER INFO BY HELICOPTERS FOR FISHERIES PROTECTION | | DEPARTMENT OF FISHERIES & OCEANS (DFO), CA. | | | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 17 | MEASURING SEA ICE THICKNESS FROM HELICOPTERS | | | ELECTROMAGNETIC INDUCTION SOUNDING EQUIPMENT & LASER PROFILOMETER | | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 18 | EVACUATION OF OFFSHORE PLATFORMS IN THE NORTH SEA | S-61, SEA KINGS, WESSEX, 214ST, 212 | | | | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 19 | GEOPHYSICAL SURVEYING BY HELICOPTER | HUGHES 500D, LAMA, S-61 | AERO SURVEYS INC. | HUMMINGBIRD ELECTRO-MAGNETIC SYSTEM, SCINTREX MAGNETOMETER, NOVATEL GPS NAV. SYSTEM | | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 20 | EARTHQUAKE DAMAGE SURVEY | | JAPAN BROADCASTING CORP (NHK) | HIGH-DEFINITION TV CAMERAS (HDTV) | | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 41 | PASSENGER TRANSPORT SERVICE (CIVIL TRANSPORT) | S61N | SAN FRANCISCO OAKLAND HELICOPTER AIRLINES, INC. | | | | 0.1 | | | | 50.9 | | 49 | | | | | | | | | | | | | | | | | 7.48 | | | | | | |

**FOOTNOTES:**

N/A - MISSION IDENTIFIED, DATA NOT AVAILABLE

OPFH - OCCURRENCE PER FLIGHT HOUR

(1) REPEATED HEAVY LIFT (RHL)

(2) 3 IN-FLIGHT, 1 WITH ROTOR STOP

(3) 1.0 FOR AIRFRAME

(4) 2.0 FOR AIRFRAME

(5) 20 LIFT/TORQUE CYCLES PER HOUR, EA CYCLE HAS 2 TORQUE SPIKES

(6) 1 LIFT/TORQUE/LANDING CYCLE PER HOUR, EA CYCLE HAS 2 TORQUE SPIKES

(7) 11 LIFT/TORQUE CYCLES PER HR, EA CYCLE HAS 2 TORQUE SPIKES

(8) 1 LIFT/TORQUE/LANDING CYCLE PER HR, EA CYCLE HAS 2 TORQUE SPIKES

# RCDT Accomplishments

## Helicopter Usage Spectrum Development

### TABLE 1. HELICOPTER USAGE S

| REF. NO. | MISSION | MODEL | ORGANIZATION/SOURCE | PECIAL EQUIPMENT | ON GROUND | | HIGE | | HOGE | | MANEUVER | | STRAI & LEV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | % | OPFH | % | OPFH | % | OPFH | % | OPFH | % |
| 1 | CAM 6 DESIGN USAGE SPECTRUM | | CIVIL AERONAUTICS | | 1.5 | | 4 | | | | 19.5 | | 64.5 |
| 2 | OVERALL SORTIE | BELL 212 | BRISTOW HELICOPTERS | | 12 | | 16 | | 10.5 | | 10 | | 49 |
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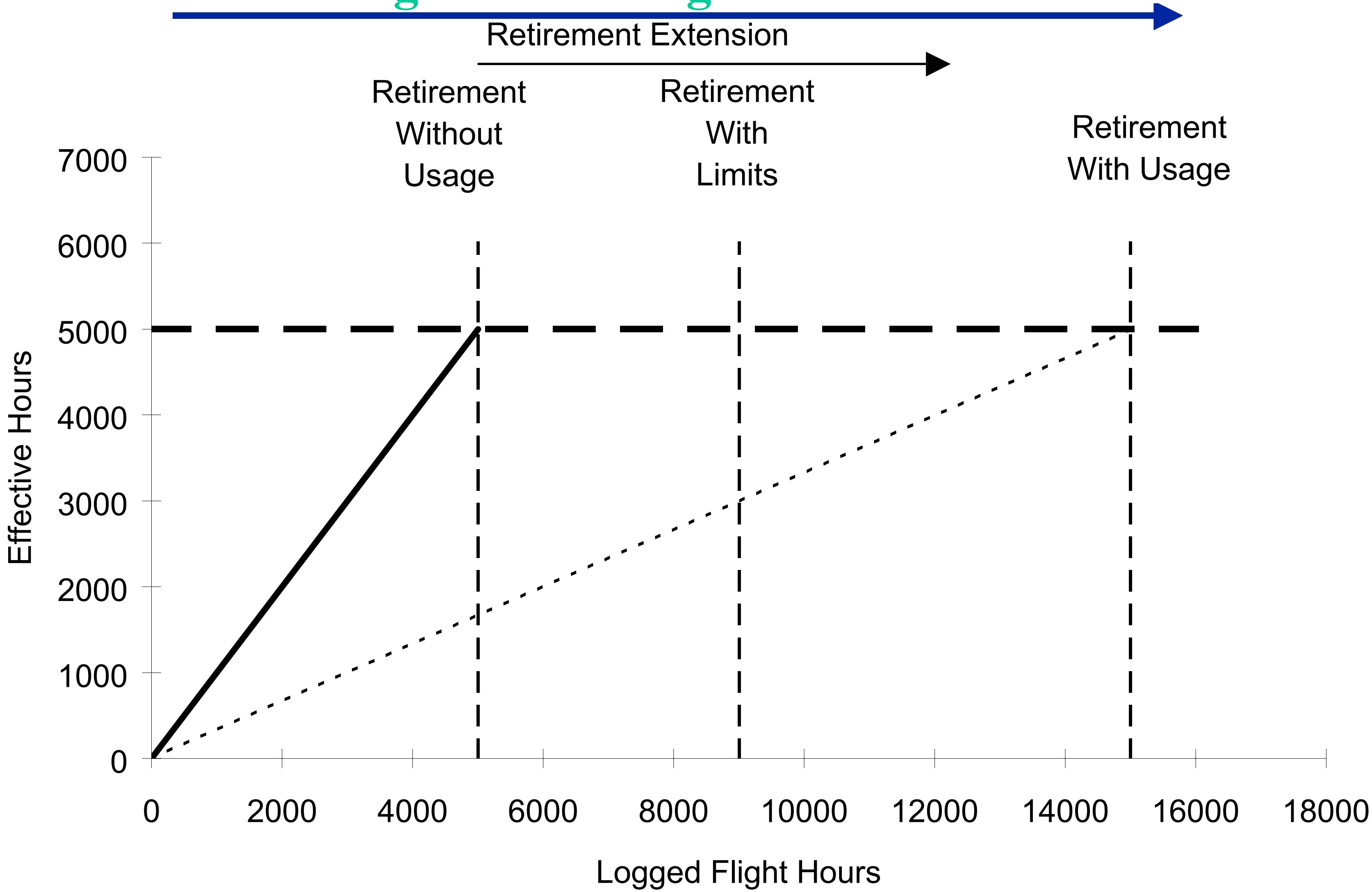
| 5 | | BELL 412 | BRISTOW HELICOPTERS | | | | | | | | 8.2 | | 61.1 |
| 6 | ATLANTA SHORT HALL | BELL 412 | PETROLEUM HELICOPTERS | | 0 | | 7.3 | | | | 28.3 | | 64.4 |
| 6 | OFFSHORE OIL SUPPORT GULF COAST MISSION | BELL 412 | PETROLEUM HELICOPTERS | | 0 | | 3.7 | | | | 14 | | 82.2 |
| 7 | UTILITY MISSION MORGAN CITY | BELL 412 | PETROLEUM HELICOPTERS | | 0 | | 2.3 | | | | 12.4 | | 85.3 |
| 8 | 412HP DESIGN USAGE SPECTRUM | BELL 412HP | BELL HELICOPTER TEXTRON | | 0 | | 4.1 | | 14.5 | | 20.4 | | 60.8 |
| 8 | 412CF DESIGN USAGE SPECTRUM | CA 412CF | BELL HELICOPTER TEXTRON | | | | | | | | | | |
| 9 | 430 DESIGN USAGE SPECTRUM | BELL 430 | BELL HELICOPTER TEXTRON | | 2 | | 4.4 | | | | 14.1 | | 78 |
| 10 | V-22 DESIGN USAGE SPECTRUM | BB V-22 | BHT & BOEING HELICOPTERS | | 1 | | 6 | | | | 33.2 | | 58.4 |
| 11 | 609 DESIGN USAGE SPECTRUM | BA 609 | BHT & AGUSTA | | | | | | | | | | |
| 12 | LYNX DESIGN MISSION MIX | LYNX | WESTLAND HELICOPTER LTD. | | 20 | | | | | | 10.4 | | 55.1 |
| 14 | HIGH PRODUCTIVITY LOGGING MISSION | K-1200 | KAMAN AEROSPACE CORP. | | | | | | | | | | |
| 14 | FIREFIGHTING MISSION | K-1200 | KAMAN AEROSPACE CORP. | UNDERSLUNG WATER BUCKET | | | | | | | | | |
| 15 | EMERGENCY MEDICAL SERVICE (EMS) | | | | | N/A | | | | | | | |
| 16 | GATHER INFO BY HELICOPTERS FOR FISHERIES PROTECTION | | DEPARTMENT OF FISHERIES & OCEANS (DFO), CA. | | | N/A | | | | | | | |
| 17 | MEASURING SEA ICE THICKNESS FROM HELICOPTERS | | | ELECTROMAGNETIC INDUCTION SOUNDING EQUIPMENT & LASER PROFILOMETER | | N/A | | | | | | | |

# RCDT Accomplishments

## Spectrum Development & Usage Monitoring Potential Benefits

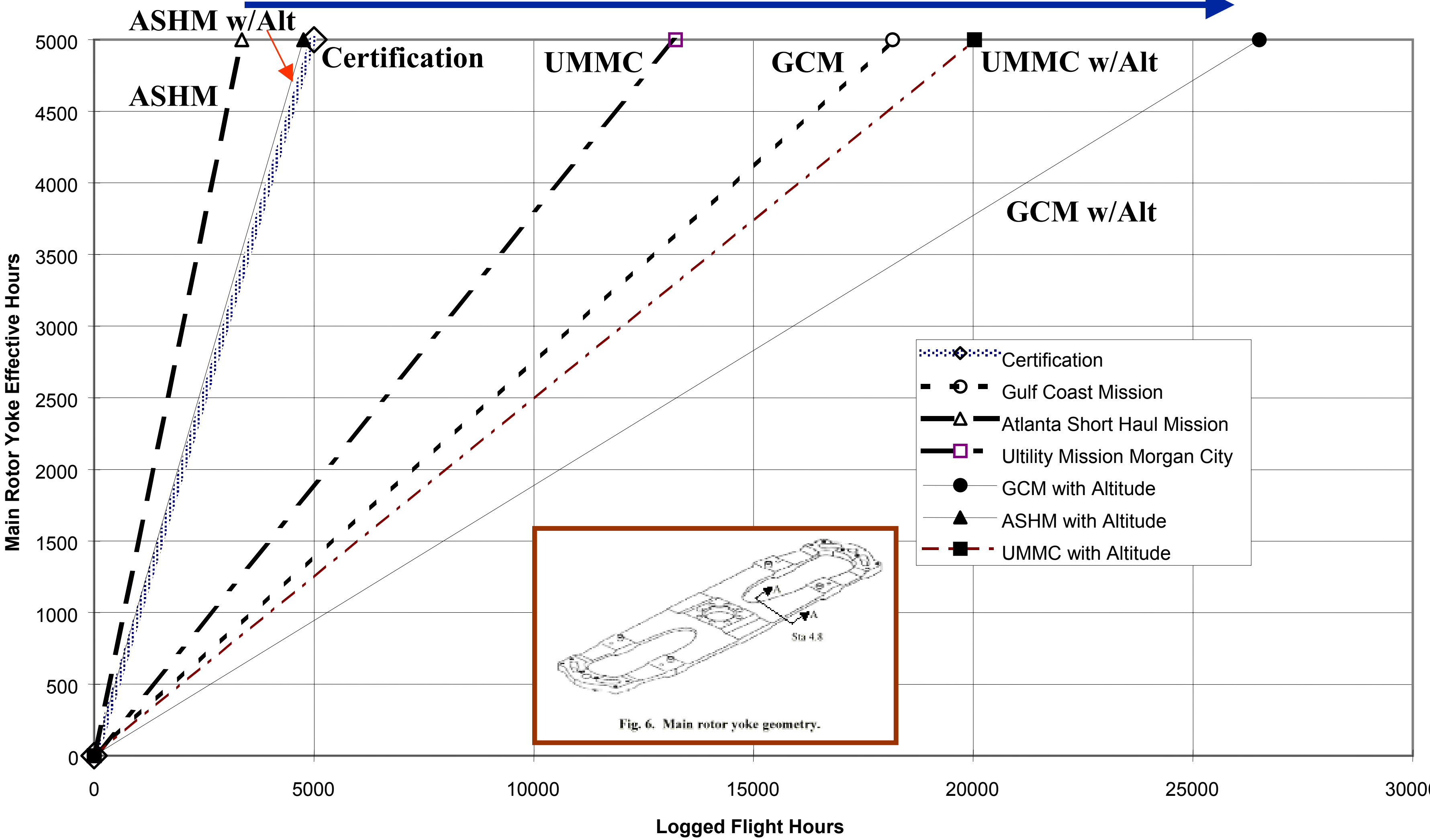
Bell Helicopter TEXTRON
A Subsidiary of Textron Inc.




**Effect on Retirement with Usage Monitoring**

# RCDT Accomplishments

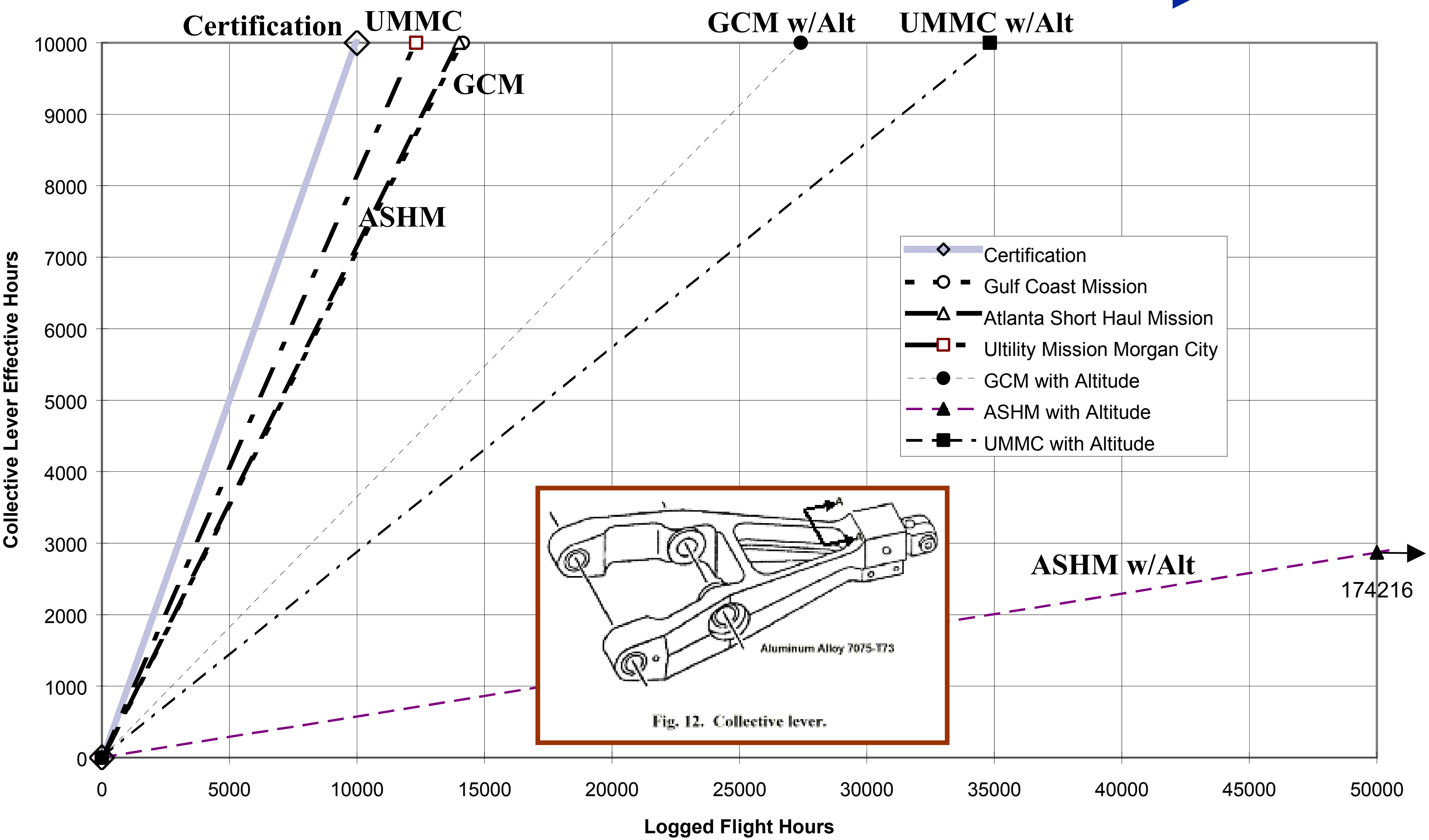
## Mission Spectrum & Usage Monitoring Life Differences




# Effective Usage - Main Rotor Yoke

# RCDT Accomplishments

## Mission Spectrum & Usage Monitoring Life Differences




# Effective Usage - Collective Lever

# RCDT Accomplishments
## Spectrum Development

- FAA is leveraging usage data from:
  - U.S. Navy on UH-60 and V-22 HUMS program.
  - Bell and PHI on Model 412 Gulf Coast Mission and others.
  - Boeing Philadelphia on commercial medium lift helicopter utility operations (logging and oil field operations and oil exploration).

# RCDT Accomplishments

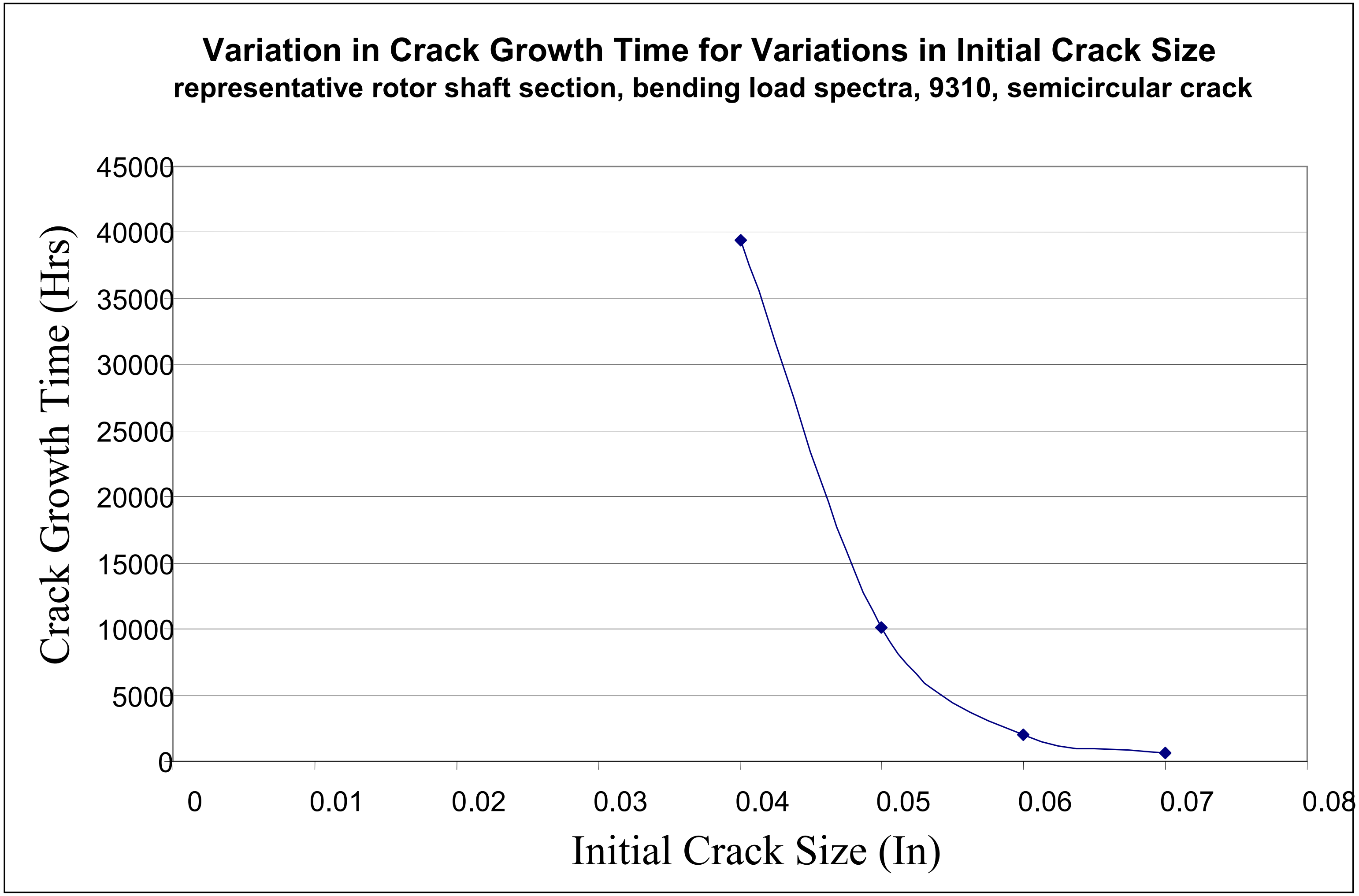
## Equivalent Initial Flaw/Crack Size (EIFS)

- Conducted studies to quantify the potential impact of variations in the assumed initial crack size on crack growth time and/or weight.

- Developed a database documenting the service experience of premature cracking and failures.

# RCDT Accomplishments

## EIFS – Sensitivity Studies



# RCDT Accomplishments

## EIFS – Sensitivity Study Observations

- Small changes in initial crack size can result in significant changes in crack growth time.
- Significant weight changes can result from some changes in initial crack size when material is added to achieve a constant crack growth time.
- Crack growth rate accelerates rapidly after the transition from a part-through crack to a through crack.

# RCDT Accomplishments
## EIFS – Damage Database

- Database that includes fields for all data items has been constructed.
- Specific damage types and clear definitions of each type to assure consistency have been created.
- User interface to the database that provides for user-friendly data entry, editing, searching, viewing, and reporting has been initiated.
- Capabilities within the database interface to easily perform elementary data analysis such as histograms and Pareto charts have been included.
- Procedures for capturing new damage data on a continual basis are being discussed.

# RCDT Accomplishments

## EIFS – Damage Database

### DAMAGE TYPE DEFINITIONS

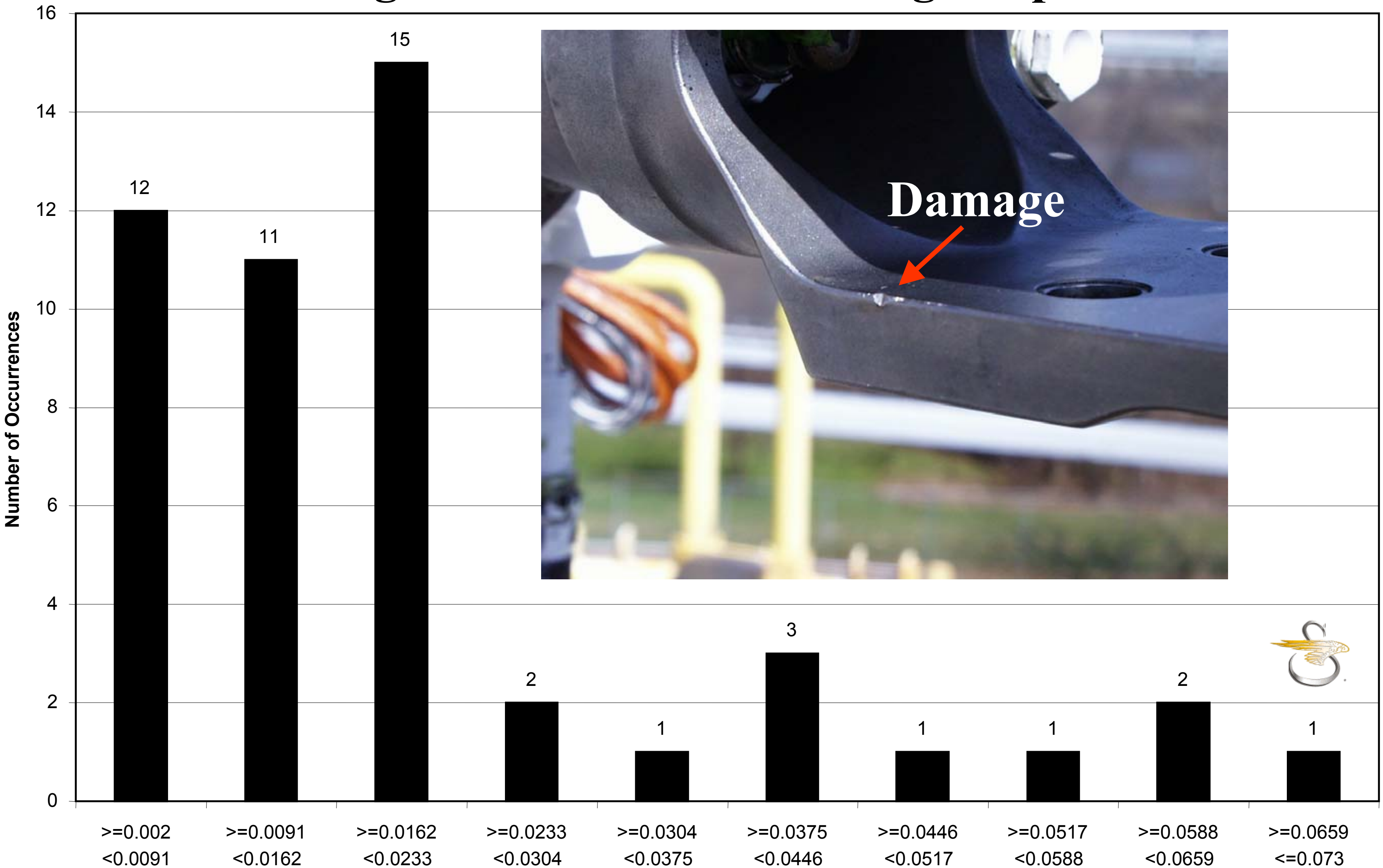
| | |
|---|---|
| **Abrasion** | Uniform removal of material over an area by action of an abrasive object or particles |
| **Bend** | A global feature in which a structure or significant portion of a structure is deformed out of plane in one direction from its original |
| **Corrosion** | Degradation of material over an area by galvanic or chemical action (pitting is considered a form of corrosion) |
| **Crack** | A surface or penetration opening or fissure with an aspect ratio (length/width) of at least 5, and little or no adjacent material deformation |
| **Dent** | A localized feature, usually associated with thin structure, where both the front and back surfaces are deformed out of plane in the same direction by action of a force contacting the front surface |
| **Ding** | A relatively small, sharp surface feature with an aspect ratio (length/width) of less than 10 where material has been displaced from a small percentage of the part thickness |
| **Gouge** | A surface feature larger and deeper than a Ding involving material displacement and/or |
| **Impression** | A feature in which surface material is displaced, leaving a relatively smooth indentation on that surface but not on the opposite (back) surface |
| **Inclusion** | An imbedded particle of material, the presence of which is not in accord with the material specification or the part drawing |
| **Nick** | The removal of material from an edge or corner of a part |
| **Puncture** | Complete penetration involving displacement and/or removal of material and resulting in an opening with aspect ratio (length/width) close |
| **Rupture** | Complete separation of a part into separate pieces |
| **Scratch** | A surface feature with an aspect ratio (length/width) of at least 10 where material has been removed by the damaging object |
| **Tear** | Complete penetration, often extending to, or initiating from, an edge of a part involving material displacement and resulting in an opening characterized by a ragged margin and an aspect ratio greater than 1, with additional material deformation adjacent to the opening |
| **Twist** | A global feature in which a structure or significant portion of a structure is deformed out of plane in multiple directions from its original geometry |
| **Void** | A cavity within the material, the size of which is not in accord with process or quality |
| **Wear** | Uniform removal of material over an area caused by relative movement of two or more mating parts of the component or structure |

Return to Previous Screen

# RCDT Accomplishments

## EIFS – Damage Database

### Histogram for Detected Damage Depth



# RCDT Accomplishments

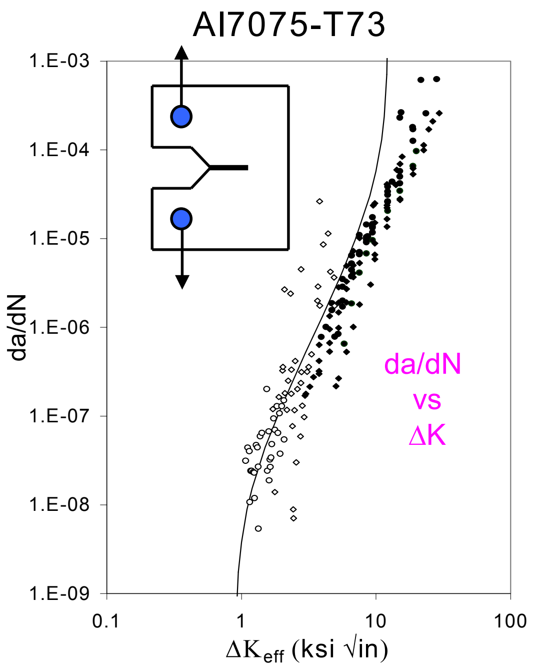
## FCG and Threshold Data (FCG/$\Delta K_{th}$ )

- Obtaining crack growth data for rotorcraft materials especially near threshold at stress ratios (R) important for rotorcraft.

- Evaluating crack growth tests methods and crack growth models (e.g. Kb Bar, C(T), closure etc.).

# RCDT Accomplishments
## FCG and Threshold Data (FCG/$\Delta K_{th}$ )

- Substantial work being done through NASA Langley (FAA-NASA IA) and Johnson (NASA-RITA collaboration) and FAA-RITA collaboration.

# RCDT Accomplishments

## FCG/$\Delta K_{th}$ – Materials Test Matrix

| Material Listing | | | | | | | | Test Information | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Material # | Definite Test Item | Wish Test Item | Wish Priority | Company | Description | Specifications | Other | Test Type | Load Ratio | Specimen Type | Orientation | Conditions | # of Spec. | Comments |
| | | | | | | | | | | | | | | |
| ***Steel*** | | | | | | | | | | | | | | |
| S1A | 1b | | | Bell | 9310 | per BHTI 299-947-302 Type 1 Carburize per BPS 4420 Class A | | da/dn, $\Delta K_{th}$ | | Kb Bar | | RT | 6 | K-Decreasing for threshold, Effect of overload on threshold |
| S1B | | | | Sikorsky | 9310 | 2 VAR | | | | | | | | |
| S1C | 5a | | | Boeing | 9310 | 9310 VIM-VAR per BMS 7-249 Type III Forged Bar or Hand Forging | 150 ksi | Spectrum | -1 to ~0.7 | CT | L-T, T-L | RT | | |
| | | | | | | | | | | | | | | |
| S2A | | | | Sikorsky | 4340 | | 150 Ksi | | | | | | | |
| S2B | | | | Sikorsky | 4340 | | 180 Ksi | | | | | | | |
| S2C | | | | Sikorsky | 4340 | | 210 Ksi | | | | | | | |
| S2D | 5a | | | Boeing | 4340 | 4340 VIM-VAR per BMS 7-250 Forged Bar or Hand Forging | 150 Ksi | Spectrum | -1 to ~0.7 | CT | L-T, T-L | RT | | |
| | | | | | | | | | | | | | | |
| S3 | | | | Sikorsky | Pyroware (X53) | | | | | | | | | |
| | | | | | | | | | | | | | | |
| S4 | 5a | | | Boeing | VASCO X2M | 5 Cr-1.4Mo-1.35W VIM-VAR Steel per BMS 7-223 Forged Bar or Hand Forging | | Spectrum | -1 to ~0.7 | CT | L-T, T-L | RT | | |
| | | | | | | | | | | | | | | |
| ***Stainless Steel*** | | | | | | | | | | | | | | |
| SS1A | | 1b, | | Bell | PH13-8Mo | forging per AMS 5629, precipitation hardened as per BPS 4140 | 205-220 ksi | da/dn, $\Delta K_{th}$ | | Kb Bar | | RT | 6 | K-Decreasing for threshold, Effect of overload on threshold |
| SS1B | | 3 | | Boeing | PH13-8Mo | AMS 5629D, H1050 per BMS 7-349 | 175-195 ksi | da/dn, $\Delta K_{th}$ | -1, 0.01, 0.5 | CT | L-T, T-L | RT | | Kmax for threshold |
| | | | | | | | | | | | | | | |
| SS2A | | 1b | | Bell | 15-5PH | per AMS 5659, TY 1 precipitation harden to 155-175 ksi per BPS 4140 | | da/dn, $\Delta K_{th}$ | | Kb Bar | | | 6 | K-Decreasing for threshold, Effect of overload on threshold |
| SS2B | | 3 | | Boeing | 15-5PH | per BMS 7-240 H1050 | 150-170 ksi | da/dn, $\Delta K_{th}$ | -1, 0.01, 0.5 | CT | L-T, T-L | RT | | Kmax for threshold |
| | | | | | | | | | | | | | | |

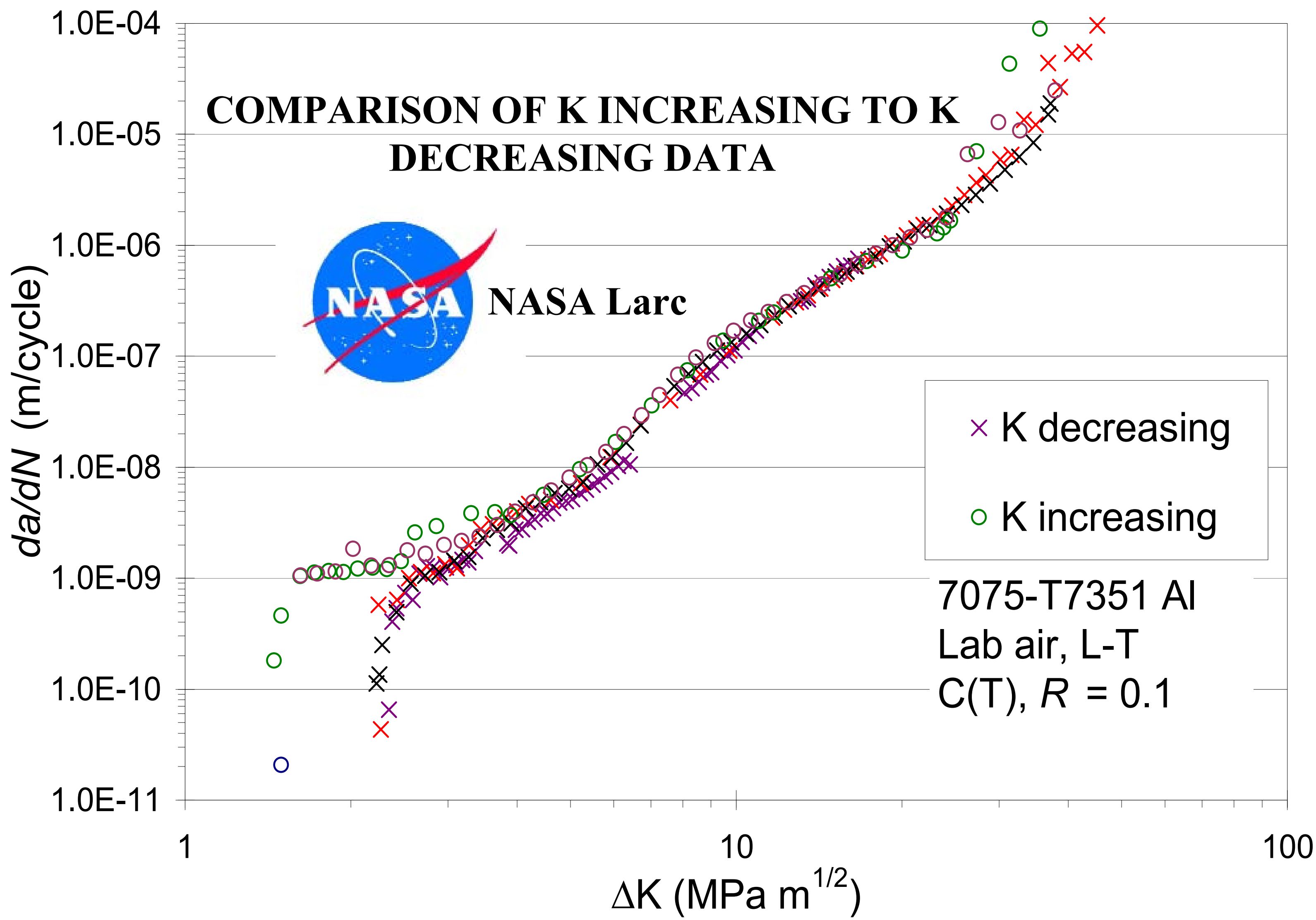
# RCDT Accomplishments

## FCG/$\Delta K_{th}$ – Materials Test Matrix

| Material Listing | | | | | | | | Test Information | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Material # | Definite Test Item | Wish Test Item | Wish Priority | Company | Description | Specifications | Other | Test Type | Load Ratio | Specimen Type | Orientation | Conditions | # of Spec. | Comments |
| A1A | 1b | | | Bell | 7050-T7452 | forging AMS 4108 (forged billet, 5 in. thick) | | da/dn, $\Delta K_{th}$ | | Kb Bar | | RT | 9 | K-Decreasing for threshold, Effect of overload on threshold |
| | | | | | | | | | | | | | | |
| A2A | | 1b | | Bell | 7050-T7451 | Plate per BMS 7-323, TY 3 (5 in. plate stock) | | da/dn, $\Delta K_{th}$ | | Kb Bar | | RT | 9 | K-Decreasing for threshold, Effect of overload on threshold |
| A2B | | 1b | | Bell | 7050-T7451 | Plate per AMS 4050 | | da/dn, $\Delta K_{th}$ | | Kb Bar | | RT | 6 | K-Decreasing for threshold, Effect of overload on threshold |
| A2C | | | | Sikorsky | 7050 | Plate | | | | | | | | |
| A2D | 5a | | | Boeing | 7050-T7452 | Hand Forging per BMS 7-214 | 68 ksi | Spectrum | -1 to ~0.7 | CT | L-T, T-L | RT | | |
| | | | | | | | | | | | | | | |
| A3A | 1b | | | Bell | 7075-T7351 | AMS QQ-A-250/12 (2.75 in. plate stock) | | da/dn, $\Delta K_{th}$ | | Kb Bar | | | 9 | K-Decreasing for threshold, Effect of overload on threshold |
| A3B | | | | Sikorsky | 7075-T7351 | plate (thick) | | | | | | | | |
| | | | | | | | | | | | | | | |
| A4A | 1b | | | Bell | 7075-T73 | forging MIL-A-22771 | | da/dn, $\Delta K_{th}$ | | Kb Bar | | RT | 9 | K-Decreasing for threshold, Effect of overload on threshold |
| A4B | | 3 | | Boeing | 7075-T73 | BMS 7-186 CL II | 68 ksi | da/dn, $\Delta K_{th}$ | -1, 0.01, 0.5 | CT | L-T, T-L | RT | | Kmax for threshold |
| A4C | | | | Sikorsky | 7075-T73 | forging | | | | | | | | |
| A4D | | | | Sikorsky | 7075-T73 | plate | | | | | | | | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| ***Titanium*** | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| T1A | | | | Bell | 6Al-4V Beta | STOA, ELI grade forged billet per MIL-T-9047, BSTOA in accordance with MIL-H-81200 | | da/dn, $\Delta K_{th}$ | | Kb Bar | | RT | 9 | K-Decreasing for threshold, Effect of overload on threshold |
| T1B | | | | Sikorsky | 6Al-4V Beta | STOA | | | | | | | | |
| T1C | 5a | | | Boeing | 6Al-4V Beta Anneal | Hand Forging per BMS 7-269 | 130 ksi | Spectrum | -1 to ~0.7 | CT | L-T, T-L | RT | | |
| | | | | | | | | | | | | | | |
| T2A | | | | Bell | 6Al-4V | Annealed per MIL-T-9047 130 ksi UTS min | | da/dn, $\Delta K_{th}$ | -0.3,0.05,0.5 | Kb Bar | | RT | 6 | K-Decreasing for threshold, Effect of overload on threshold |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| ***Magnesium*** | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| M1A | | 3 | | Boeing | Ze41A-T5 | | 26ksi | da/dn, $\Delta K_{th}$ | -1, 0.01, 0.5 | CT | L-T, T-L | RT | | Kmax for threshold |

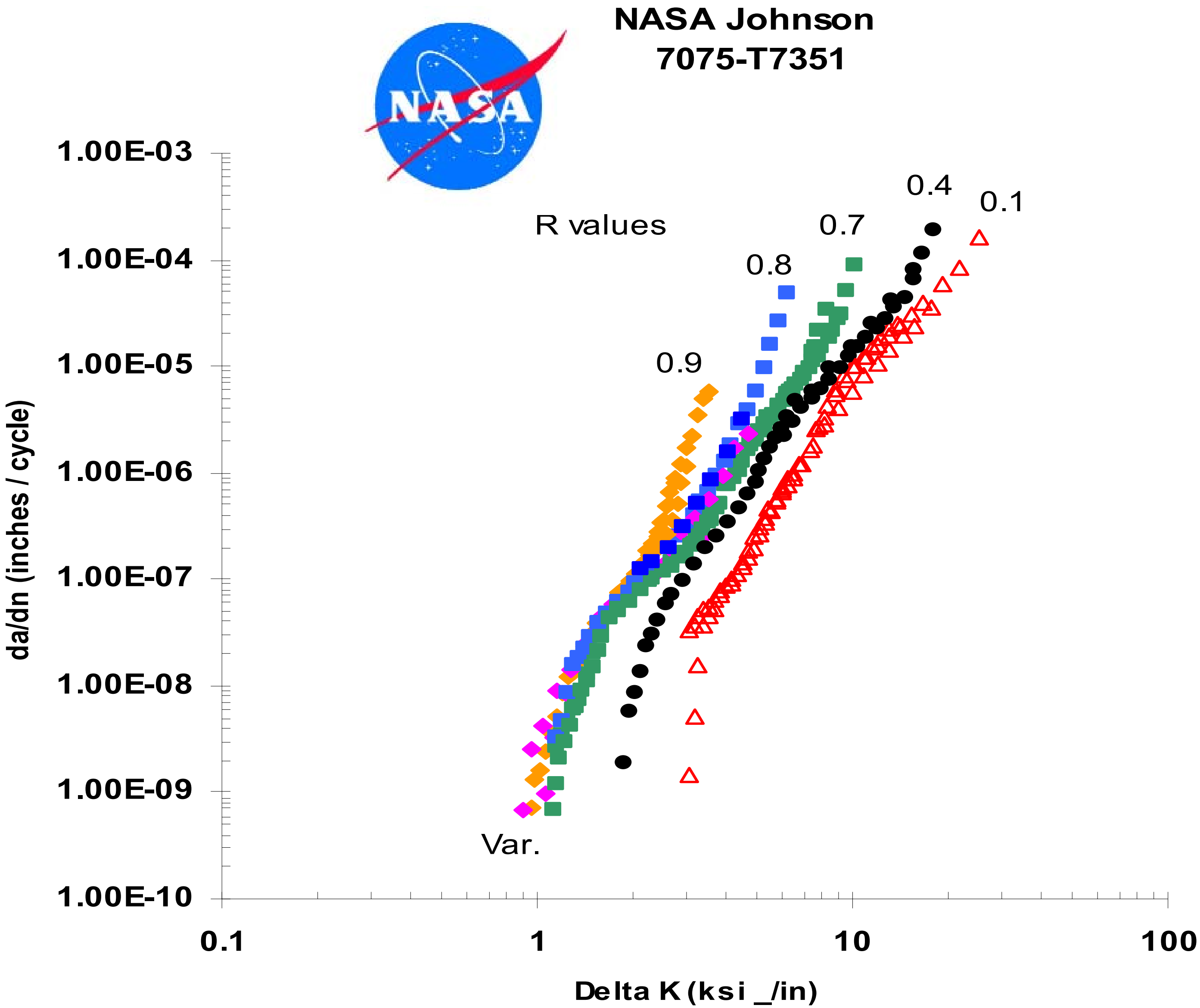
# RCDT Accomplishments

## FCG and Threshold Data (FCG/$\Delta K_{th}$ )



# RCDT Accomplishments

## FCG and Threshold Data (FCG/$\Delta K_{th}$ )



# RCDT Accomplishments

## FCG and Threshold Data (FCG/$\Delta K_{th}$ )

- $\Delta K_{th}$ values from the standard load reduction test method potentially give higher threshold values due to elevated closure effect.

- FCG and threshold data testing will continue for the next three years at a high level of effort.

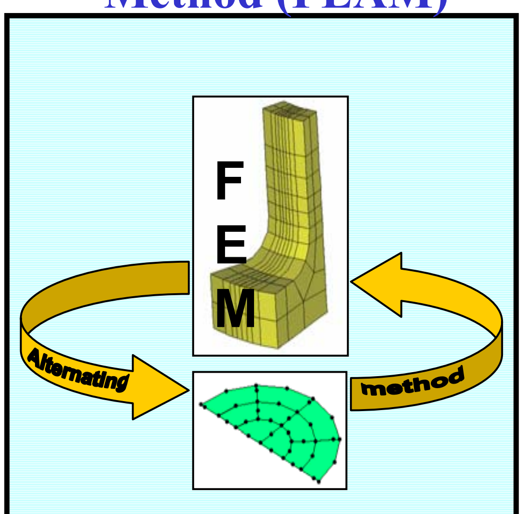
# RCDT Accomplishments

## Crack Growth Analysis

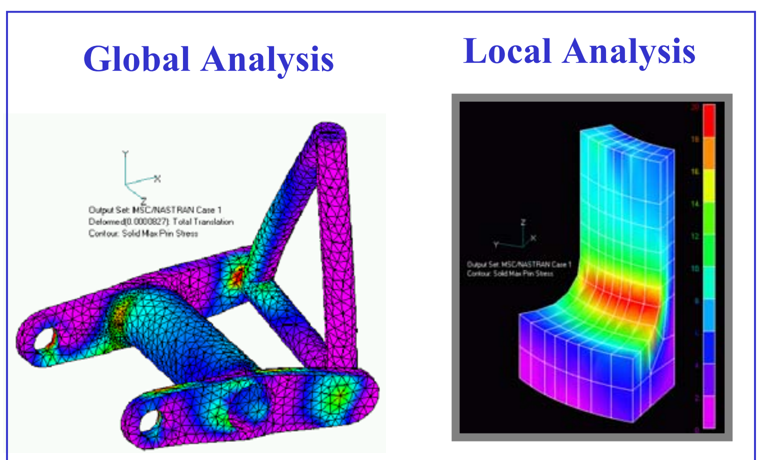
- Developed 2D Elastic Finite Element Analysis Method (EFEAM) and 3D Symmetric Galerkin Boundary Element Method (SGBEM) computational tool.

- Compared results with standard industry crack growth codes (AFGROW, NASGRO, BEASY, FRANC3D etc.)

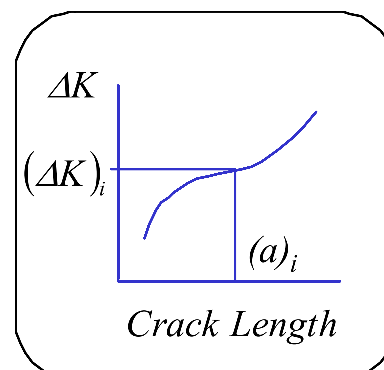
**Finite Element Alternating Method (FEAM)**




**Automated Global Intermediate Local Evaluation (AGILE)**




**SIF Calculation**



# HUMS Accomplishments
## Data Rates/Parameters Determination

- From the V-22 and H-60 data, military specific maneuvers were removed for assessment of commercial spectrum data rates.
- Minimum parameter set established to recognize all flight regimes.
- For the H-60, a study performed to determine the parameters necessary to identify damaging maneuvers.
- Functional Hazard Assessment and Usage Hazard Analysis completed.

# Future Plans

- ✈ Increase Government (NASA, DoD) collaboration in RCDT & HUMS R&D.
- ✈ Expand academia involvement in rotorcraft research.
- ✈ Continue to work with RC industry on RCDT.

# Summary

- **Motivation:** Improvements in continued airworthiness of aging and newly designed aircraft and the reduction of direct operating costs are the major drivers for the implementation of DT technology.

- **Progress:** FAA research has made major achievements in the DT and HUMS technologies needed for RC.

- **Future:** Major challenges include nonlinear fracture mechanics implementation, probabilistic and risk determination, technology transfer, and, ultimately, the use of HUMS and DT technology.